Experimental Investigations on Magnetic Abrasive Finishing of SS 304L

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Abstract

Magnetic Abrasive Finishing (MAF) is a super finishing technique, employs the magnetic force and magnetic abrasive for finishing variety of engineering materials. This paper presents the development of experimental setup to carryout MAF operations in a flat Stainless Steel grade 304L material. Experimentation was planned according to Taguchi's L16 (4^2) design of experimentation technique. The different cutting conditions selected for the investigations are: voltage applied to electromagnet, machining gap, rotational speed of electromagnet and mixing ratio (Fe+; Al_2O_3). Surface finish and percentage improvement in surface finish (%Δ R_a) were estimated after each experiment. From the experimental results it was found that the average surface finish value has been achieved as low as 0.09 µm.

Keywords*: MAF, Taguchi method, SS 304L, Surface finish*

1 Introduction

Finishing operations in manufacturing of precise parts are always of concern owing to their most critical, labour intensive and least controllable nature. Traditional fine finishing of precision components is a challenging and time consuming operation in manufacturing. High precision finishing methods are of utmost importance and are the need of present manufacturing scenario. Conventionally, pre-machined surfaces are subjected to finishing operations like grinding, super finishing, lapping, honing, etc. If properly carried out, these abrasive machining processes can produce a surface of higher quality with a controlled surface roughness combined with a desirable residual stress distribution and freedom from surface and sub-surface damages [1]. New advanced finishing processes were developed in last few decades to overcome limitations of traditional finishing processes in terms of higher tool hardness requirement and precise control of finishing forces during operation.

The application of magnetic field in the control of manufacturing processes in general and finishing in particular has become of interest. Magnetic abrasive finishing (MAF) is a technology in which a magnetic field forms a magnetic abrasive tool composed of abrasive particles and possessing ferromagnetic properties. Some obvious MAF advantages over existing methods of abrasive finishing include (i) preliminary performance tools (grinding wheels, abrasive sticks and bells, and so on) are not necessary; (ii) abrasive tools can be quickly replaced; (iii) an abrasive tool can be reshaped without bond destruction when finishing ferromagnetic parts of machines of complicated shapes; and (iv) because of the distance of the magnetic field, it is possible in some cases to treat inaccessible surfaces, for example, the inner surface of tubes [2]. The schematic representation of the plane MAF process is shown in Figure 1.

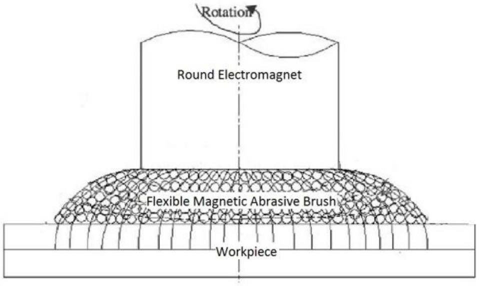


Figure 1: Plane Magnetic abrasive finishing [1]

The basic principle of the MAF process was studied by Shinmura et al [3] and it was reported that material removal and surface finish value (R_a) increase as the magnetic abrasive particle diameter increases. Jain et al [4] studied MAF of non-magnetic stainless steel with the use of loosely bounded MAPs has been carried out. It was concluded that working gap and circumferential speed of workpiece are the parameters which significantly influence the material removal and surface finish. Shinmura et al [5-8] found that magnetic flux density and working gap greatly affect the surface roughness and stock removal. Further they reported that an experimental study on plane workpieces using the MAF process. They observed that the surface roughness value decreases with increasing finishing time upto a certain limit of time beyond which no further improvement was noticed.

Ching et al [9] studied the magnetic abrasive finishing process in free-form surface operations using the taguchi experimental design, considering the effect of magnetic field, spindle revolution, feed rate, working gap, abrasive, and lubricant. By this study they revealed that MAF provides a highly efficient way of obtaining surface finish.

This paper deals with the design and fabrication of MAF Setup for plane surfaces. Using this setup, experiments have been conducted to evaluate the MAF process performance. The main objective of the present investigation is to study the effect of voltage applied to electromagnet, machining gap, rotational speed of electromagnet and mixing ratio (Fe^+; Al_2O_3) on change in surface finish and percent improvement in surface finish specifically when using loosely bounded MAPs.

2 Development of MAF setup

In the present work, an experimental set-up is developed for carrying out MAF process in a vertical milling machine. Details of the set-up are explained in the following sections.

2.1 *Electromagnet and mandrel assembly*

MAF Set-up consists of an electro magnet, mandrel, sleeve, and lock-nut. The specifications of the magnet are 50 mm in diameter and 30 mm in length. And its magnetic field varies from 0.05 to 0.45 Tesla depending upon the working gap. The lifting capacity of the magnet is 11 kg. The magnet is attached to the machine spindle using a mandrel. Figure 2 illustrates the electromagnet and mandrel assembly and Figure 3 shows the photographic view of MAF spindle assembly.

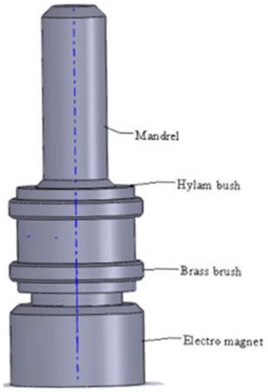


Figure 2: Electromagnet and mandrel assembly

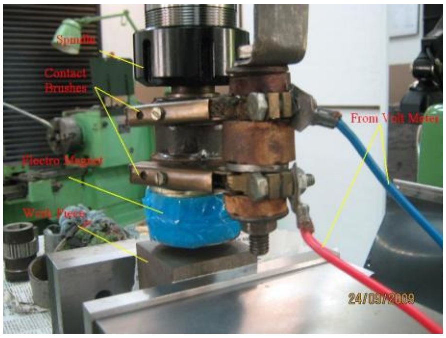


Figure 3: Photographic view of MAF spindle assembly

2.2 *Experimental set-up*

The Electromagnet and mandrel assembly is attached to the spindle of a milling machine as shown in Figure 4. Current is supplied to the electromagnet using carbon bush placed on sleeve and electromagnetic field is created to carry out MAF process.

Figure 4: MAF setup in a milling machine

3 Experimental details

3.1 *Workpiece and abrasive details*

In this work, MAF process is carried out using the developed experimental setup on SS 304L flat workpiece. The chemical composition of workpiece material is tabled in Table 1.

Table 1: Chemical composition of SS 304L

Alloying Elements	Percentage (%)
Chromium	18.37
Nickel	8.190
Manganese	1.800
Copper	0.580
Silicon	0.540
Phosphorus	0.039
Nitrogen	0.037
Carbon	0.021
Sulphur	0.019
Fe	Balance

Aluminium oxide is used as an abrasive medium and it is mixed with the Fe particles in 4:1 weight ratio. The average grain size of the abrasive and iron powders are 60 µm and 100 µm, repectively.

3.2 *Taguchi experimental design*

Taguchi experimental design is considered as a highly effective design for the determination of influential parameters of a manufacturing process. In the present investigation, an orthogonal array (OA) L16 (4^2) for a two level factor is considered for determining the effect of process parameters on surface finish. Pilot experiments are performed to find the suitable range of input parameters. Table 2 shows the process parameters and their levels. The parameters selected for the present investigation are: voltage applied to electromagnet, machining gap, rotational speed of electromagnet and mixing ratio (Fe+; Al_2O_3). Table 3 shows the constant parameters of the process.

Table 2: Process parameters selected and their levels

Process parameters	Unit	Levels	
		1	2
Voltage	V	15	20
Machining gap	mm	1.5	2
Rotational speed	rpm	270	540
Mixing ratio ($Fe^+ : Al_2O_3$)	Ratio	4:1	3:2

Table 3: Constant Parameters

Parameter	Value
Feed rate	15 mm/min
Machining Time	30 min

3.3 *Experimental procedure*

The following procedure was adopted during experimentation on the MAF set-up.

1. All workpieces are initially finished by surface grinding process to have almost the same initial Ra value.
2. Then the workpiece is fixed in machine vice such that the parallelism is maintained between flat-faced electromagnet and work piece by using dial gauge. Then the required machining gap is set by using slip gauges.
3. Machining gap is filled with magnetic abrasive and the electromagnet is magnetized. Due to the magnetic field the mixture of abrasive and iron powder is attracted towards magnet and forms a brush.
4. The spindle speed and feed rate are set as per the design of experiment and finishing is carried out on stainless steel specimens up to 30 minutes.

3.4 *Measurement of surface finish*

The average surface roughness values of the stainless steel specimens are measured before and after MAF process using Mitutoyo surftest equipment. A sampling length of 0.8 mm with a characteristic length of 4 mm is chosen for measurement. The Ra value is measured at three different locations on the workpiece and averaged. The average R_a values before and after MAF are summarized in Table 5. It can be observed that there is a reduction in surface roughness of the specimens due to MAF process.

The measurements of R_a have been done in the selected area in the direction perpendicular to the lays obtained during grinding (for initial R_a) and MAF (for final R_a) processes. The reduction in Ra value (ΔR_a) and percentage improvement in surface finish ($\%\Delta R_a$) values have been calculated using the Eqs. (1) and (2) and also calculated values for the each experiment is tabulated in Table 4.

$$\Delta R_a = Initial\, R_a\, valuve - Final\, R_a\, Value \qquad (1)$$

$$\%\Delta R_a = \frac{\Delta R_a}{Initial\, R_a\, Value} \text{ x } 100 \qquad (2)$$

Table 4: Percentage improvement of surface roughness of steel specimens at various process parameters

Expt. No.	Voltage (V)	Machining gap (mm)	Speed (rpm)	Mixing Ratio	Avg. R_a Before MAF (μm)	Avg. R_a After MAF (μm)	Δ R_a (μm)	%Δ R_a
1	15	1.5	270	4:1	0.73	0.54	0.19	26.03
2	20	1.5	270	4:1	0.72	0.42	0.3	41.67
3	15	2	270	4:1	0.89	0.76	0.13	14.61
4	20	2	270	4:1	0.6	0.44	0.16	26.67
5	15	1.5	540	4:1	0.41	0.29	0.12	29.27
6	20	1.5	540	4:1	0.57	0.22	0.35	61.40
7	15	2	540	4:1	0.8	0.62	0.18	22.50
8	20	2	540	4:1	0.48	0.29	0.19	39.58
9	15	1.5	270	3:2	0.66	0.45	0.21	31.82
10	20	1.5	270	3:2	0.47	0.23	0.24	51.06
11	15	2	270	3:2	0.96	0.79	0.17	17.71
12	20	2	270	3:2	0.56	0.34	0.22	39.29
13	15	1.5	540	3:2	0.68	0.46	0.22	32.35
14	20	1.5	540	3:2	0.4	0.09	0.31	77.50
15	15	2	540	3:2	0.71	0.53	0.18	25.35
16	20	2	540	3:2	0.54	0.32	0.22	40.74

4 Results and discussion

In this section, effect of process parameters such as voltage applied to electromagnet, machining gap, rotational speed of electromagnet and mixing ratio (Fe^+; Al_2O_3) on percentage improvement in surface finish are discussed.

4.1 *Effect of process parameters on percentage improvement in surface finish*

Figure 5 illustrates the main effects of process parameters on percentage improvement in surface finish. The main effects of the voltage and working gap on the responses are quite significant as compared to rotational speed and mixing ratio. Table 5 shows the average of each response characteristic (means) for each level of each factor. The table also shows the ranks based on Delta statistics, which compare the relative magnitude of effects. The Delta statistic is the highest minus the lowest average for each factor. The ranks are assigned based on Delta values; rank 1 to the highest Delta value, rank 2 to the second highest, and so on. The ranks indicate the relative importance of each factor to the response.

Table 5: Response table for means

Level	Mixing ratio	Speed (rpm)	Machining gap (mm)	Voltage (V)
1	32.72	31.11	43.89	24.95
2	39.48	41.09	28.31	47.24
Delta	6.76	9.98	15.58	22.28
Rank	**4**	**3**	**2**	**1**

Abrasive mixing ratio*:* From the Figure 5 (a) it is observed that high %Δ R_a is obtained at mixing ratio 3:2. It is due to the fact that flexible magnetic abrasive brush contains more abrasive particles than at 4:1 mixing. Hence, micro cutting increases resulting in reduced surface roughness value (increased in %Δ R_a).

Rotational speed of electromagnet*:* The %Δ R_a increases with the increase in rotational speed of the electromagnet (Figure 5(b)). It could be due to by increasing the speed, material removal by abrasives in unit time increases resulting in smoother surface.

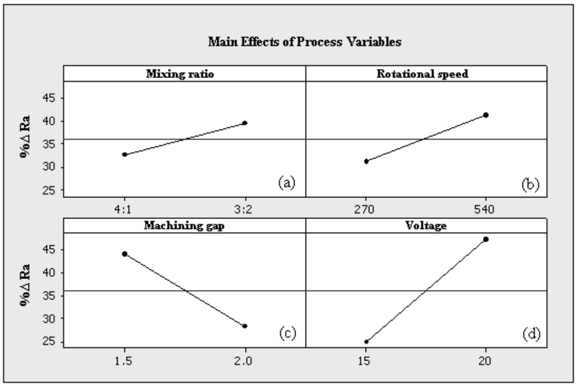


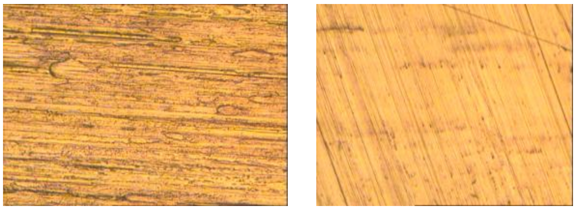
Figure 5: Main Effect of process parameters on %Δ Ra

Effect of machining gap*:* Figure 5(c) shows that as the machining gap (working gap between the electromagnet and workpiece) increases the %Δ R_a decreases. It is due to the fact that as the working gap increases the flux density of the flexible magnetic abrasive brush decreases.

Effect of Voltage*:* The %Δ R_a increases with increase in voltage because of the fact that higher voltage to the electromagnet generates more number of lines of magnetic force, and therefore higher flux density in a specified gap (Figure 5(d)). Hence, strength as well as area of contact of the magnetic brush with workpiece increases with increase in voltage, leading to a greater number of indentations into the workpiece.

4.2 *Optical microscopic image*

Figure 6 show the optical microscopic image of the workpiece before and after MAF process. Microscopic views have revealed that the abrasives are random in shape hence the variation in the depth of cut is expected due to the shape and orientation of protruding abrasive particles.



(a) (b)

Figure 6: Optical microscopic (200X) view of SS304L (a) before MAF (b) after MAF

It is quite clear from Figure 6(a) that deep cutting marks left by the grinding operation have been removed and replaced by the new texture generated during the MAF process, Figure 6(b). The lay lines have become smoother and are spaced farther apart after MAF process. The smoothness of the lay lines can be related to the surface roughness values. Smooth lay lines produced by finer grains (Figure 6(b)) result in a lower R_a value of the finished surface.

5 Conclusions

This paper demonstrated the development of an experimental setup for MAF process for producing improved surface finish on stainless steel specimens.

Taguchi experimental design method is followed for identifying the key operating parameter of the MAF process.

From the experimental results, voltage is found to be the most significant parameter followed by machining gap. However, the effects of mixing ratio number and rotational speed of electromagnet seem to be very small as compared to voltage and machining gap.

From the main effects of the process parameters, it is concluded that within the range of parameters evaluated, a high level of voltage (20 V), a low level of working gap (1.5 mm), a high level of rotational speed (540 rpm), and mixing ratio (3:2) are desirable for improving the surface finish of the stainless steel specimens.

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